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Forecasting how residential urban form affects the regional carbon savings and costs of retrofitting and decentralized energy supply

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HIGHLIGHTS

- An innovative model for testing combinations of spatial planning and decentralised energy supply.
- An improved method of modelling the spatial variability of energy consumption per dwelling type.
- Shows how spatial planning would affect the future carbon reduction of decentralised supply.
- Forecasts the future carbon reduction and costs of retrofitting and decentralised supply.
- A method of forecasting how residential space would affect the suitability of decentralised supply.

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ABSTRACT

Low carbon energy supply technologies are increasingly used at the building and community scale and are an important part of the government decarbonisation strategy. However, with their present state of development and costs, many of these decentralised technologies rely on public subsidies to be financially viable. It is questionable whether they are cost effective compared to other ways of reducing carbon emissions, such as decarbonisation of conventional supply and improving the energy efficiency of dwellings. Previous studies have found it difficult to reliably estimate the future potential of decentralised supply because this depends on the available residential space which varies greatly within a city region. To address this problem, we used an integrated modelling framework that converted the residential density forecasts of a regional model into a representation of the building dimensions and land of the future housing stock. This included a method of estimating the variability of the dwellings and residential land. We present the findings of a case study of the wider south east regions of England that forecasted the impacts of energy efficiency and decentralised supply scenarios to year 2031. Our novel and innovative method substantially improves the spatial estimates of energy consumption compared to building energy models that only use standard dwelling typologies. We tested the impact of an alternative spatial planning policy on the future potential of decentralised energy supply and showed how lower density development would be more suitable for ground source heat pumps. Our findings are important because this method would help to improve the evidence base for strategies on achieving carbon budgets by taking into account how future residential space constraints would affect the suitability and uptakes of these technologies.

1. Introduction

The UK Climate Change Act 2008 has legislated for decarbonisation by implementing a system of 5-year carbon budgets to achieve an 80% reduction in targeted greenhouse gas emissions by 2050 relative to 1990 levels. The "Low Carbon Transition Plan" implemented in 2009 includes increasing the proportion of gas, nuclear and renewable energy supply and reducing the proportion of the more polluting fuels such as coal. The national demand for electricity may double by 2050, due to population growth and the electrification of heating and road transport. Hence there is a daunting

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amount of investment needed in energy supply infrastructures, including replacing a quarter of power capacity by 2020 for security of supply, and a target of 30% of electricity in 2020 to come from renewable sources.

Buildings account for over 40% of all CO_2 emissions and there have been various initiatives to improve their energy efficiency. The requirement for energy conservation was first introduced into the UK building codes in 1976 as 'Part L' of the Building Regulations and since then there has been only a step by step increase in energy efficiency standards. Also, around two-thirds of dwellings that currently exist were built prior to 1976. Consequently much of the UK housing stock has been built with low energy efficiency performance. In recent years there have been a number of government schemes to incentivise retrofitting, most recently the 'Green Deal'. This provided subsidised loans for energy efficiency improvements but it had low uptake from households and the scheme closed in 2015.

The Code for Sustainable Homes (CfSH) initiative [1] was introduced in 2006 to achieve a progressive step-change in building practice with the aim of all new dwellings being 'zero carbon' by 2016 ('Level 6'). Developers were allowed discretion on how to achieve the required level of CfSH, such as energy efficient building fabric, decentralised supply technologies, and 'allowable' solutions such as bio-fuel carbon offsets or contributions to offsite electricity generation [2]. This would typically include discussions with the local planning authority, which have responsibility for sustainable development [3]. The UK government recently withdrew the CfSH and in March 2015 announced a new National Technical Standard that will be more easily attainable with the aim of simplifying and speeding up the development process. This new technical standard will be broadly equivalent to CfSH Level 4 which was the greatest reduction in CO_2 emissions achievable by energy efficient building fabric alone.

These building standards for homes do not take into account transport, which accounts for a similar magnitude of CO_2 emissions per capita to the buildings. Car travel varies considerably between different area types with people in rural areas travelling around twice as far per year by car than those who live in urban conurbations [4]. Therefore, location of development is an important factor affecting the overall energy consumption and carbon emissions of a household.

The UK Future of Heating government report [5] proposed that decentralised energy supply will make a substantial contribution to future CO_2 reduction, with heat pumps and hybrid boilers supplying the majority of future domestic heating. The strategy for meeting future carbon budgets in the Committee on Climate Change (CCC) advisory reports to the UK government relies heavily on these decentralised technologies for domestic buildings [6]. However, their report on low carbon heat scenarios [7] and the DECC government consultation on a domestic renewable heat incentive scheme [8] both identified cost effectiveness and uncertainty about whether properties have the space required for installation as important barriers to the uptake of these technologies.

Evidence for these strategies is from methods that can be broadly divided into either techno-economic energy system models or more 'bottom up' building stock energy models. The RESOM model is an example of an energy system model and was used to provide evidence for the Future of Heating report [9]. It disaggregated dwellings into standard dwelling typologies and whether they would be in rural or urban areas but with no explicit representation of the variability of their plot size or floor space. MARKAL is a widely used energy system model [10] and Dodds [11] found that adding extra dwelling typologies made relatively little difference to its forecasts because it operates at an aggregate scale. He concluded that these energy system models need to be combined with building stock models to account for the spatial variability of urban form.

There are numerous examples of building stock energy models [12,13]. These use typologies that correspond with national housing survey data classifications such as dwellings types, age bands, building fabric and heating systems [14]. These models have been developed to estimate energy demands and consumption for the building stock at regional scale. These models distinguish between dwelling types but not how they vary on outdoor space or how floor space varies spatially within the region per dwelling type. Their land and floor space can vary greatly, which affects energy consumption and their potential for decentralised energy conversion. This is partly due to differences in household preferences and wealth and also the differences in land values between areas. An increase in land value due to regeneration or improved access to jobs and services creates development pressures for higher density. This transformation through property conversions and redevelopment further increases the diversity of the housing stock. It would be advantageous for urban energy models to represent this variability [15].

Pereira & Assis [16] showed how changes in household energy consumption are spatially correlated with changes in income, and numerous studies have shown that human factors account for a substantial amount of the variability of energy use [17–19]. Greater affluence tends to increase the demand for floor space and may diminish the financial motivation to reduce energy consumption. Conversely, people on low incomes may be less likely to adopt energy supply technologies [20]. Governance and community involvement will be important for the implementation of distributed energy systems [21].

There are clearly interrelationships between the availability of space and the suitability of decentralised technologies. A study by Blum et al. [22] estimated the potential CO_2 reduction of ground source heat pumps (GSHP). This was based mainly on regional household energy demands and soil conditions but not the availability of residential space. GSHP have lower capital costs if there is sufficient outdoor space for horizontal loops but they can also be installed as more expensive vertical loop systems so long as there is enough access space for installation [23]. The Future of Heating report suggests that GSHP will initially be more suitable for dwellings off the gas grid in outer areas because these have more space available and replacing their carbon intensive heating systems would have environmental benefits. However, heat pumps are low temperature systems that are more suitable for well insulated properties. Ground source heat pumps may be most suitable for new build because if installed as part of the construction process and if the new dwellings have under floor heating they can operate at a more efficient temperature. Micro-CHP may be a suitable alternative in areas with insufficient space for heat pumps so long as there is sufficient indoor space for the equipment. However gas-fuelled CHP systems only achieve a relatively small reduction in carbon emissions and their cost effectiveness depends on the temporal balance of the demand for heat and power and is greater if the power is fully utilised within the dwellings [24].

The above examples illustrate that the suitability of decentralised energy technologies needs to be considered at the building-scale because their cost effectiveness will depend on the combination of energy demand and built form characteristics. However, decisions on policy support such as public subsidies, regulations and research and development are taken at national scale. This poses a difficult challenge because these strategies have a long time horizon and so rely on forecasts.

Forecasting the future urban densities is best done using a socio-economic urban model, such as land use and transport interaction (LUTI) models which are static aggregate models of the location choice of industry and households. The inputs include economic and demographic projections and the constraints on land and transport. Until recently very few LUTI models included energy and buildings but they have the potential to provide an energy modelling framework [25]. An early case study recognised the potential of these models for estimating the energy use by building and transport but only used average values of energy consumption per unit of floorspace [26]. More recently, the SOLUTIONS research project forecast the energy use and carbon dioxide emissions of buildings and transport for case studies of three English city regions [27]. Average densities were converted into four dwelling typologies and their energy consumption was estimated using the UK Standard Assessment Procedure ratings. However, this did not include modelling the potential for decentralised energy conversion.

Regional-scale land use-transport forecasting models can provide a top-down simulation of the supply and demand for land and floor space at the building parcel scale [28]. Some include GIS-based micro-scale modelling of the floor space types and rental values of land parcels, but not the size and variability of buildings and land. The reliance on mapping limits their capability to forecast the future urban form. In another example, a regional scale macro-model was linked to an UrbanSim model [29]. This simulated neighbourhoods as 2.25 hectare grid cells chosen from a set of 25 development types further defined by a range of residential units and non-residential floor space to create typical contiguous urban areas. Each land parcel was intended to represent the typical spatial layout of urban form but this leads to difficulties matching the data sources at different scales and makes the macro-model very resource intensive to create and operate over large areas. These parcel-based representations of urban areas have been used to link urban layouts to infrastructure modelling, particularly storm water modelling [30]. There has also been extensive research on computer graphic simulation methods using geospatial data to represent urban form and these have been used for energy analysis such as the potential for PV [31,32] and urban energy planning [33]. Although these detailed GIS based methods are useful for studying existing areas, they lack forecasting capabilities and are difficult to reconcile with regional scale models.

An integrated modelling framework is needed that combines socioeconomic forecasts at city region scale with a representation of the variability of the residential land, building stock and occupancies, thereby allowing integration with models of energy use and decentralised energy supply options. This paper presents an innovative method of achieving this important objective. It converted regional forecasts of urban densities into the variability of residential building stock, which was then approximated by systematically selecting sets of discrete 'tiles'. Each tile represented dwellings of a particular type, floor space and plot size. Retrofitting and decentralised supply scenarios were modelled for each tile type depending on the area type and development type. This method has produced findings on their regional suitability for reducing CO_2 and how this would vary depending on the area type and residential density.

The main contribution of this paper is a method of taking into account the variability of domestic floor space and outdoor space when forecasting the suitability of decentralised energy technologies. This would increase the reliability of evidence used for policy advice on meeting future carbon budgets and the paper will be of interest to policy makers, utility companies, researchers and consultants.

2. Method

2.1. Case study and regional forecasting model

This research was carried out as part of a case study of the London, East of England and South East regions, known as the wider south east of England (WSE). A 'Trend' planning policy was estimated for the forecast year of 2031 by combining national planning projections with local government planning policies. The planning projections were from the National Trip End Model (TEMPRO) which were based mainly on the LUTI modelling part of the UK National Transport Model [34]. The density targets for new-build in the local authority districts were obtained from the Local Development Frameworks. Appendix B provides further information about the method of estimating the Trend forecast.

These estimates of future residential land availability for 2031 were combined with the household forecasts to estimate the future residential density per electoral ward (wards are the smallest electoral areas in the UK averaging around 5500 people). Each ward was given an area type classification of central, urban, suburban or rural derived from Office for National Statistics (ONS) ward classifications [35]. Fig. 1 shows how the percentage of wards per area type varied with the average residential density per ward, as calculated using the residential land from the Generalised Land Use Database [36] and dwellings from the ONS 2001 Census data.

Technology scenarios were tested for year 2031 to show how the future CO_2 emissions and cost effectiveness of the technologies would vary within the case study area.

A sensitivity test was carried out for an alternative spatial planning policy and tested using a LUTI model [37] by varying the inputs on the availability of land for residential development.

2.2. Converting the density forecasts into urban form

An innovative 'tiles method' was devised by Hargreaves [38] to convert the average residential densities per ward into an estimate of the building stock. This method was developed by analysing the English House Condition Survey (EHCS) data [39]. It found that, after firstly disaggregating the housing stock by dwelling type, area type, morphology, and age band, the frequency distribution of plot density could be represented by the gamma distribution and its

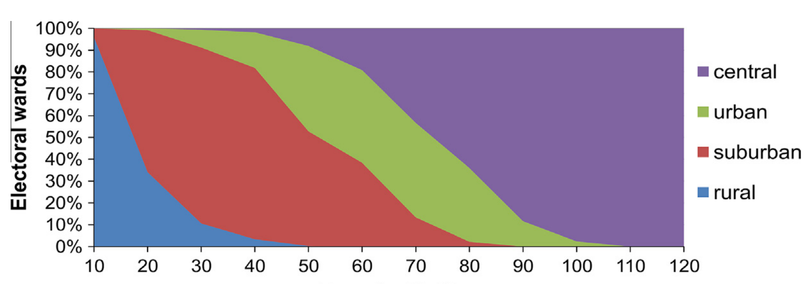

Fig. 1. Percentage of ward types versus average residential density.

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shape parameter could be calibrated using the EHCS data. Plot-density was calculated as the inverse of the 'plot size' per dwelling (a.k.a. 'lot size'). The convenient mathematical properties of the gamma distribution allow the scale parameter to be calculated from this calibrated shape parameter and the mean plot density. Hence the frequency distribution of plot-density could be estimated and this was then systematically approximated by selecting from a set of generic one-hectare 'tiles' (Fig. 2). This can include fractions of one-hectare to best match the theoretical plot density distribution. They are therefore able to match the regional urban model outputs on land areas, dwellings and population, without the inconsistencies between the spatial scales of parcel-based methods. The tiles are an abstract representation of the housing stock and residential land, rather than aiming to provide an impression of the future neighbourhood layout.

The tile density, dwelling dimensions and plot size were designed based on the EHCS data. Samples of residential areas similar to each tile type were identified and studied to estimate the associated areas of roads, pathways and communal areas to include in the design of the tiles. These discrete 3D tiles were very useful as a shared medium for multidisciplinary research on energy, water and waste.

The main advantage of the tiles over previous building typologies is that they include the residential land as well as building dimensions and so each tile type could encapsulate both demand and the potential for decentralised supply. The potential supply from district network schemes was inferred from the combination of area type, tile type and development type. This gave an indication of the potential contribution at regional scale of district scale systems, even though the method had insufficient detail for site-specific design.

There were three different versions of each tile type to represent the development types of either 'Existing-areas'; 'Intensification' by redevelopment; or development on 'New-land'. The energy consumption, CO_2 emissions and costs were estimated per tile type using building-scale models for each technology scenario. The tiles method thereby combined the impacts of built-form, occupancies, retrofitting and energy supply at the building scale within a regional socioeconomic modelling framework. This integrated modelling framework could be used to forecast the effects of spatial planning, transport investment and decentralised technology strategies. The research subsequently applied a similar method to non-domestic buildings but this was not completed in time to test mixed-use development.

2.3. Modelling the energy demands of dwellings

The dwelling energy demands were estimated using the Domestic Energy and Carbon Model (DECM) for predicting the energy consumptions and carbon dioxide emissions of the existing English housing stock [40]. This national building energy model includes the adoption of an occupancy pattern model derived from the ONS household and employment status data, which improves the accuracy of the estimation in space heating energy use. The DECM is based on EHCS data which includes the building dimensions, fabric, occupancies and age bands for each dwelling type. Based on the findings, a set of predictive charts were developed which can provide rapid estimations of the effect of various energy efficiency measures on dwelling energy demands and carbon dioxide emissions taking into account the potential rebound effect. This allowed the building energy model to estimate impacts of retrofitting measures for each combination of tile type and occupancy. The three adjustment factors in the model are external temperature; total floor area; and number of occupants. Socio-economic classification is not directly used in the energy adjustment but it is used in the regional model to forecast density at the ward level and hence the floor areas. The energy use was then adjusted based on the variation in floor area. The average occupancies per tile type were proportionally adjusted per ward to match the population forecast. The climate for 2031 was estimated from the UKCP09 medium emissions 90% probability scenario [41].

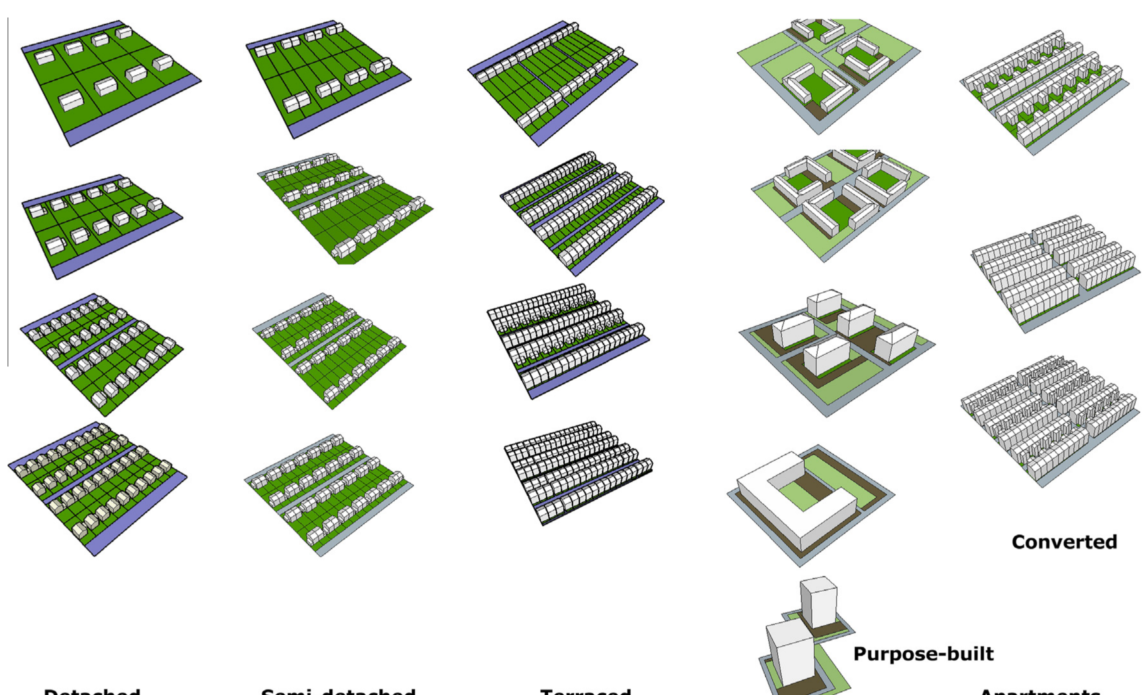

Fig. 2. Schematic illustration of the tiles.

2.4. Modelling the energy supply scenarios

The energy demands by time of year for heating, cooking and power were used as inputs to the selection and modelling of the energy supply technologies, which was based on similar methods to the Ashford Renewable Energy Feasibility study [42]. The uptakes and system size of the decentralised technologies were estimated per tile type depending on the building and plot dimensions and the likely cluster size which was inferred from the development type and area type. The performance of the technologies also took into account the likely availability of local supply resources such as conventional infrastructures and solar insolation. The initial uptake assumption for 2031 was that the technologies would replace 30% of the component of conventional supply relevant to that chosen technology so that there would be at least 70% of conventional balancing supplies. For example, biomass & gas would supply around 30% of heat, whereas the CHP technologies would supply around 30% of electricity. There would be interdependency between the calculated percentages of decentralised heat and electricity which affects percentage of supply for heating and electric. Sensitivity testing could easily be carried out for different uptake assumptions as further research. The energy supply was modelled using established methods which were generalised for the range of temporal energy demands, building orientations, shading, soil conditions, climate and occupancy types within the case study regions. The Suitability Table in Appendix A shows which tile types would be suitable for each technology based on the energy supply method and assumptions. Hence, the sizing and costing of the supply systems took into account the building scale and community-scale characteristics. Total CO_2 emissions for energy supply were estimated on the basis of grid and fuel emission factors (kg/kW h). Further details of the method can be found in Appendix C.

2.5. Assessment method

Cost effectiveness was calculated for each scenario as a relative measure against the most appropriate reference case to represent the cost of achieving a one tonne reduction in CO_2 emissions per year, and compared with a carbon price of around £70/tonne in 2031 [43]. The costs of the decentralised scenarios were calculated based on their annual capital and operating costs that would be additional to the internal equipment costs for conventional supply, spread over the lifetime of the technology which ranged from around 20 years to 30 years. The equivalent 2009 annual capital and operating costs of the retrofitting measures and supply technologies were estimated based on a social discount rate of 3.5% and the methods in the HM Treasury Green Book on Appraisal and Evaluation [44]. These were the actual social costs without including any subsidies such as feed in tariffs. The total annual energy supply cost per tile also included the annual household bills for the conventional component of energy supply based on prevailing price structure for household gas and electricity supply in 2009. Future costs may differ in real terms from those in 2009 but the future costs are uncertain. For example, the costs of decarbonising the grid may to some extent be offset by improvements in power generation efficiency; and although technologies such as photo-voltaic (PV) panels are reducing in price, their building installation and control equipment is a substantial additional cost that will not reduce at the same rate. There was no attempt to model; the impacts on prices if fuel demands exceed supply; externalities such as air pollution; or the economic benefits attributable to local generation for reducing the demands on conventional supply. The range of simplifying assumptions above mean that the final results for the relative costs of different options in the future are illustrative and are not intended to be forecasts. The study seeks to show how the performance of different technologies is affected by urban form and density, and so uncertainty about future technical advances and cost reductions has not been included. These known technologies and costs provided a useful initial basis for calculating the cost effectiveness of the technologies. Sensitivity testing by varying these parameters could easily be carried out using this integrated modelling framework as part of further research.

The outputs per tile type for assessment included the reduction in carbon dioxide emissions per annum; land required; percentage of decentralised supply for heat and electricity; capital and operating costs; and the annual energy supply cost.

3. Scenario testing for buildings and energy

3.1. Building fabric and energy efficiency

The research had a 'base year' of 2009. Those dwellings that existed in 2009 that were forecast to still exist in 2031 are referred to as 'Existing' dwellings. (Appendix B explains how the rate of redevelopment of existing residential areas was modelled depending on the spatial policy and the area type.) The Existing dwellings were tested with and without energy efficiency retrofitting to investigate how changes in energy demands would affect the findings for the decentralised supply. The energy demand modelling assumed that the retrofitting uptake would be around 40% of dwellings [45]. Jones et al. [46] found that 'shallow' retrofitting has a positive rate of return but 'deep' retrofit was not cost effective. Therefore, 'low-CO_2' and 'low-cost' scenarios were tested: The 'low-CO_2' retrofitting included more expensive measures, such as internal and external wall insulation and double glazing; whereas the 'low-cost' retrofitting would use only lower cost measures, such as loft and cavity wall insulation.

Dwellings built from 2009 onwards were referred to as 'New-build.' All of the future New-build dwellings were assumed to meet a high level of energy efficiency achievable by building fabric alone, equivalent to the advanced building fabric package of the Code for Sustainable Homes (CfSH) Level 4 because this was the guidance in place at the time of carrying out this research.

Dwellings built to the UK Building Regulations Part L 2006 were used as the reference case to assess whether the extra building costs for this CfSH standard [47] would be cost effective.

3.2. Energy supply

The decentralised energy supply options consisted of building-integrated technologies and community scale systems. The building-integrated technologies included micro-combined heat & power (micro-CHP), biomass boilers, ground source heat pumps, and photovoltaic panels (PV). The community scale systems included CHP, district heating (DH) and larger biomass boilers [48]. The selection and analysis was based on the best available technologies in year 2011 without speculating on future improvements.

The selection of technologies for each scenario took the following approach. It was driven by firstly considering the characteristics of energy demands such as the balance of heat and electricity loads and the concentration of demand. It took into account the building energy demands and whether the dwellings would be as-Existing, retrofitted-Existing, or New-build. It also considered whether new dwellings would be by Intensification of residential areas or on New-land because this affects the suitability of supply technologies. It then used a rules-based method to choose suitable technologies. The following broad selection principles were used because the development types would affect their feasibility and installation costs:

- Retrofitting existing areas: Focus on building-integrated technologies.
- Intensification by redevelopment: Include community-scale technologies.
- New development areas: Networked heat and CHP first, and then building integrated technologies.

For example, CHP technologies were selected for central areas due to space constraints; whereas technologies that enable renewable energy conversion were selected in lower density areas. District heating was not tested for Existing dwellings because the costs of installation would be higher than for New-build and the suitability of existing areas would need to be considered on a site specific basis.

There were three main energy supply scenarios:

- ‘Low-CO_2’ – to achieve a large reduction in carbon dioxide emissions.
- ‘Low-cost’ – to reduce carbon dioxide emissions but only using lower cost technologies.
- ‘Highly-electric’ – include thermal energy technologies powered by electricity from the grid.

The ‘low-CO_2’ scenario included PV in residential areas for renewable power supply as well as the low carbon heating technologies, whereas PV was not part of the ‘low-cost’ and ‘highly-electric’ scenarios. These three scenarios were tested for the future Existing dwellings and New-build.

The New-build dwellings are expected to be much more energy efficient than Existing dwellings. This will limit the further reduction in CO_2 emissions that could be achieved by decentralised heating and so some of the more expensive technologies may not be cost effective. Therefore, New-build included an extra ‘highly electric’ scenario that included resistive heating because this technology may become more suitable as heat demands reduce and the electric grid is decarbonised.

Appendix A summarises the technologies and percentages of supply for each scenario. The technologies were chosen to represent the main types of decentralised technology that would be broadly applicable to the specified combinations of area and development type. Horizontal-loop ground source heat pumps were tested as the example of heat pump technology because their suitability is more directly related to spatial form than air source heat pumps and less dependent on building energy efficiency. (None of the scenarios included the trading of surplus energy conversion back to the grid.)

4. Results

4.1. Dwellings and technologies year 2031

The carbon dioxide emissions per capita in the WSE case study area for Existing dwellings in 2031 are shown in the top left-hand map of Fig. 3 (the Existing dwellings are those forecast to still remain in 2031 that existed in 2009). The emissions would be substantially greater in the outer suburban and rural areas because these lower density areas have more floor space per capita and a greater proportion of the less energy efficient dwelling types, such as detached and semi detached houses. The other maps arranged from middle to bottom RH show how the retrofitting for energy efficiency and then the inclusion of decentralised supply would progressively reduce CO_2 emissions. This is particularly evident

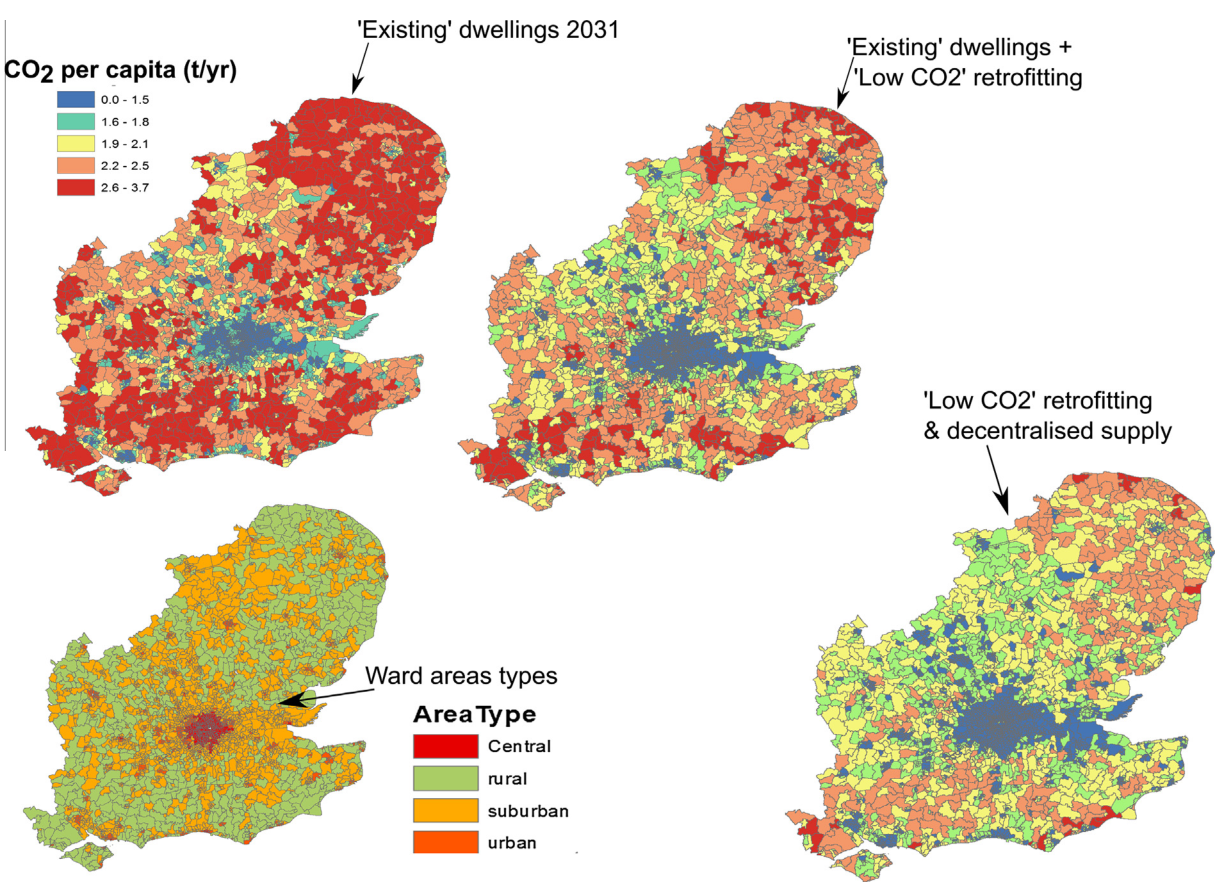

Fig. 3. CO_2 emissions per capita for Existing dwellings in year 2031 (ward area types also shown).

in the lower density areas where dwellings have a greater potential for energy efficiency improvements and more garden and roof space for low carbon technologies. However, these measures are progressively more expensive and it is questionable whether they would be cost effective compared to other ways of reducing carbon emissions. Similar maps could also be produced for the dwellings on New-land or by Intensification of existing areas, and for costs as well as CO_2. The differences between area types are less noticeable for New-build because these dwellings would be much more energy efficient than Existing dwellings.

The following results compare the costs and CO_2 reductions of some of the technologies. They compare the investment costs for installing the alternative energy supply options with the costs to households of purchasing conventional electricity and gas for use in central heating: As such the study has not undertaken a full social optimisation of this part of the energy system [49,50]. On this private investment basis, many of the technologies tested would not be cost effective compared to the conventional supply without policy support. The technology uptakes are expected to be fairly low due to the conditions explained in Section 2.4 and in Appendix A. Hence the average changes per capita would be quite small at regional scale. These are outputs per capita and as such take into account both the dwelling characteristics and their occupancies. Dwellings in higher density areas tend to be smaller with fewer occupants and so per capita outputs would be greater if all other values per dwelling were equal.

Fig. 4 shows the findings for the retrofitting of Existing dwellings for energy efficiency. Fig. 4a shows that Existing dwellings would have much lower CO_2 emissions per capita in 2031 than in 2009. This is mainly due to decarbonisation of the electric grid, but also partly due to a warmer climate and our assumption that the average efficiency of boilers will improve by around 10% over this period. There would be a substantial reduction in emissions per retrofitted dwelling. However, the assumption of 40% uptake of retrofitting over the forecast period means that there would only be modest reduction in average CO_2 emissions per capita. The 'low cost' retrofitting would have a positive return on investment in all areas (Fig. 4c) because the energy savings outweigh the capital cost. The deeper 'low-CO_2' retrofitting would only have a financial return on investment in low density areas but would be within the £70/tonne carbon price at all densities.

Table 1 summarises the findings for the decentralised technologies that were chosen to represent the main types of decentralised supply for Existing dwellings.

Although the PV would not be cost effective, some of the heating technologies may approach cost effectiveness and are compared in Fig. 5. All of the technologies would increase energy costs and therefore would not be financially attractive to developers and households without policy support. The only technology tested that would have a carbon abatement cost within the £70/tonne was the micro-CHP & gas but its CO_2 reduction would be minimal. The biomass and GSHP technologies could substantially reduce CO_2 emissions per individual dwelling but after taking into account their respective uptake assumptions they would have only a marginal impact on reducing the average CO_2 emissions per capita in the case study regions.

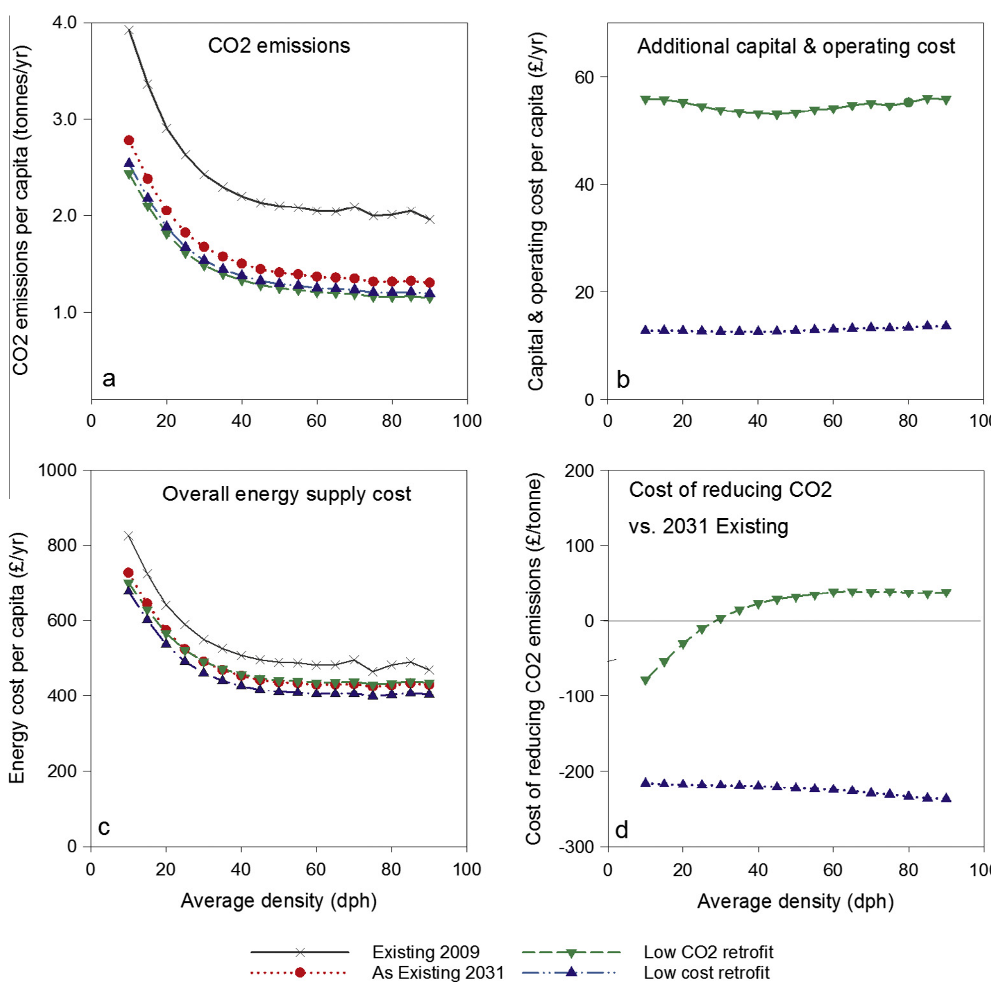

Fig. 4. Retrofitting of Existing dwellings to improve energy efficiency – results for 2031.

Table 1
Cost effectiveness of the technologies for Existing dwellings in 2031.

Technology	Area type			
	Rural	Suburban	Urban	Central
Biomass & gas	x	x	x	
GSHP (individual)	x	x	x	
Micro-CHP & gas				√
PV	x	x	x	

Key: √ – cost effective. x – not cost effective.

Although not cost effective per se, the heat pump and biomass heating technologies of would be cost effective if bundled with low cost retrofitting because the energy savings from the retrofitting would offset the costs of the decentralised supply.

The results for New-build dwellings in 2031 are shown in Fig. 6. This shows that buildings with CfSH level 4 fabric would reduce costs compared to those built to Part L 2006 Building Standards because the energy cost savings would outweigh the extra building costs. The New-build was optimistically assumed to achieve CfSH advanced Level 4 fabric and it can be seen by comparing Figs. 4 and 6 that their CO_2 emissions would be around two-thirds lower than those of Existing dwellings in 2031. The further reductions achievable by decentralised supply are therefore quite small. None of the energy supply technologies tested would be cost effective on a private investment basis. GSHP was the technology that came closest. Micro-CHP & gas may have been cost effective but was not tested because district heating was selected to represent the CHP technologies for New-build in Central areas. The large gas CHP would reduce CO_2 emissions but the construction costs of district heating would make it financially unattractive for widespread general application. However, it may have been suitable if assessed for specific sites with a significant heat source and clustering of new development. The resistive heating scenario would be more expensive than conventional heating due to the supply cost of electricity being higher than gas. The decarbonisation of the electricity grid means that by 2031 the CO_2 emissions of resistive heating would be very similar to conventional gas heating and for clarity is not shown in Fig 6. Resistive heaters may become cost effective in the longer term as the electricity grid is further decarbonised. However, it would still be financially unattractive to households unless there is a relative decrease in electricity prices compared to gas. PV would not be cost effective based on the 2011 costs and performance data but is become increasingly cost effective as the technology advances.

4.2. Validation of results

The energy consumption estimates of this tiles method were compared with the 2009 energy consumption data [51] published by the UK Department of Energy and Climate Change (DECC). This data was domestic electricity and gas consumption for the ONS Lower Super Output Areas (LSOA), which range in size from 400 to 1200 households. The validation was carried out for the West Midlands region as part of the Liveable Cities research project.

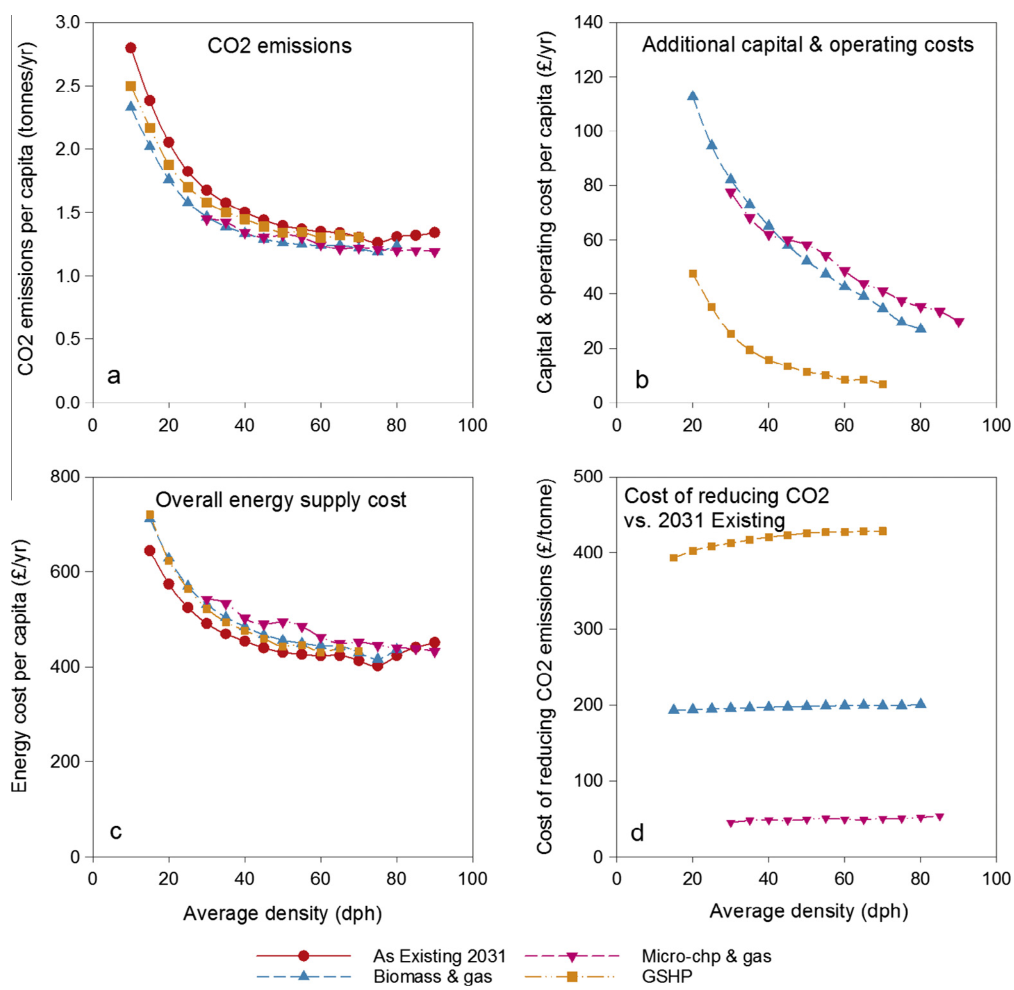

Fig. 5. Examples of heating technologies tested for Existing dwellings in 2031.

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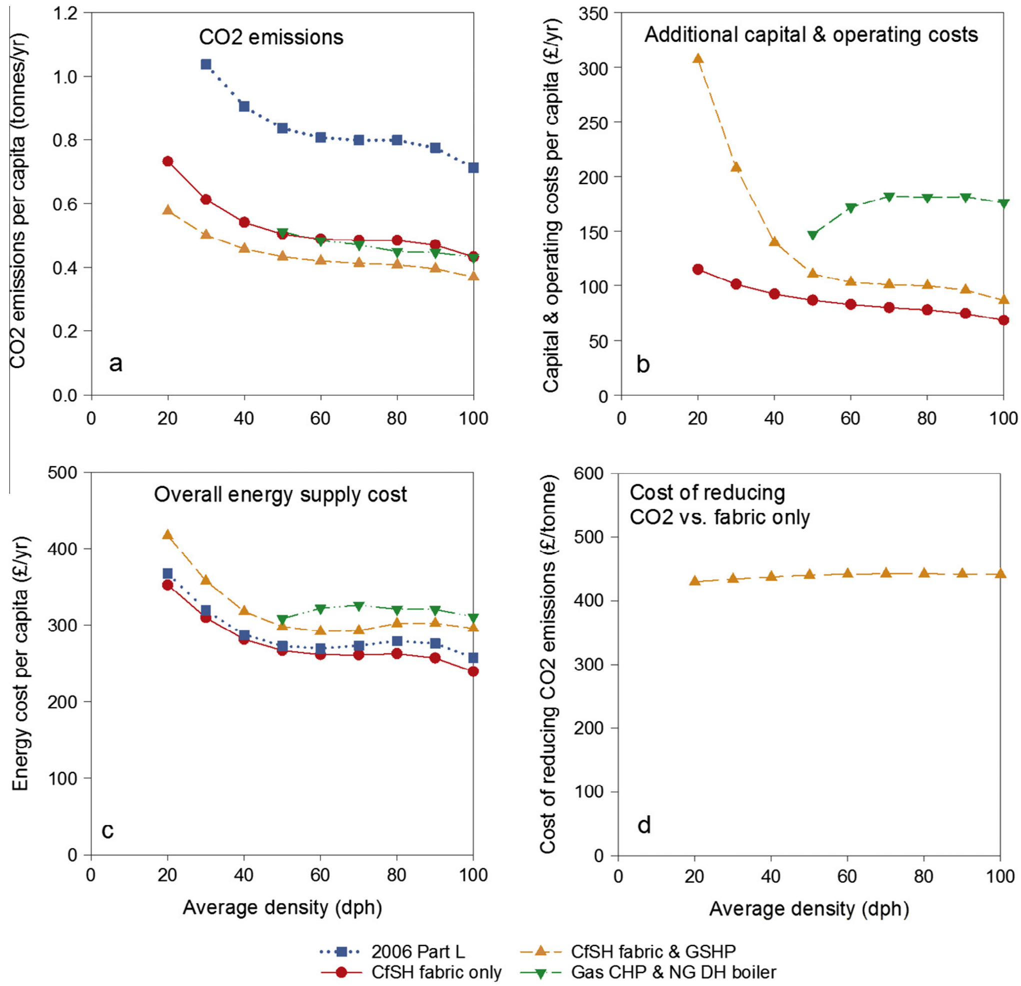

Fig. 6. Results for New-build dwellings in 2031.

Applying the tiles to this different region from the original case study makes the validation more independent and reliable. The tiles were calculated per ONS Output Area, which average around 125 households. The inputs to the tiles calculation were the GLUD data on residential land and the numbers of dwelling from the ONS Census. The tile outputs were then aggregated to the LSOA level.

The energy data per dwelling varies greatly between the LSOA areas, especially for gas consumption which is strongly correlated with floor space. Fig. 7a shows the estimates of gas consumption using dwelling typologies (detached, semi-detached, end-terrace, mid-terrace and apartments) and Fig. 7b shows the estimates using the tiles method. The gas consumptions for the average typologies were from the DECM model [40] and compared against those calculated for the tiles using the same DECM model. It can be seen that the gas consumption estimates using the tiles method fits the data much better than using the average dwelling types ($R^2 = 0.49$ versus $R^2 = 0.20$). This is particularly evident at the extremes of either low or high density and shows that the tiles method makes the estimates of energy consumption more accurate for spatial modelling because the tiles better represent the spatial variation in floor space per dwelling type. The estimates using either the tiles or standard dwelling types were both within 2% of the DECC data totals at regional scale.

Unfortunately there was no equivalent large data set available to validate the findings for the energy supply technologies. However, the tiles method is likely to result in an even bigger improvement for decentralised energy supply because land and roof space is even more variable per dwelling type than floor space. This can be seen by comparing the dimensions per tile type in Appendix A.

4.3. Sensitivity test of the impact of spatial planning policy on decentralised supply

The following sensitivity test compared the impacts of two alternative spatial planning scenarios on decentralised energy supply. These provisional forecasts were for the current Trend and a more Market-led spatial planning policy (other policies could be tested and assessed in more detail but this is beyond the scope of this paper). Fig. 8 compares these forecasts for 2031 with dwellings in year 2001 per area type. It shows that most of the growth is expected in the suburban areas and a 'Market-led' relaxation of planning constraints would result in slightly higher growth in these suburban areas and correspondingly less in central and urban areas. Most of the Market-led development would be on New-land whereas the Trend would have more redevelopment through intensification of existing residential areas. Both options would have local planning policy constraints to prevent sprawl but more of the Market led development would take place in lower density areas.

Fig. 9 compares the CO_2 emissions per capita for the 'Low-cost' and 'Highly-electric' decentralised energy supply scenarios for New-build. The Low-cost scenario would have district heating (DH) fuelled by natural gas in urban areas and by biomass & gas in suburban and rural areas. The Highly-electric scenario would

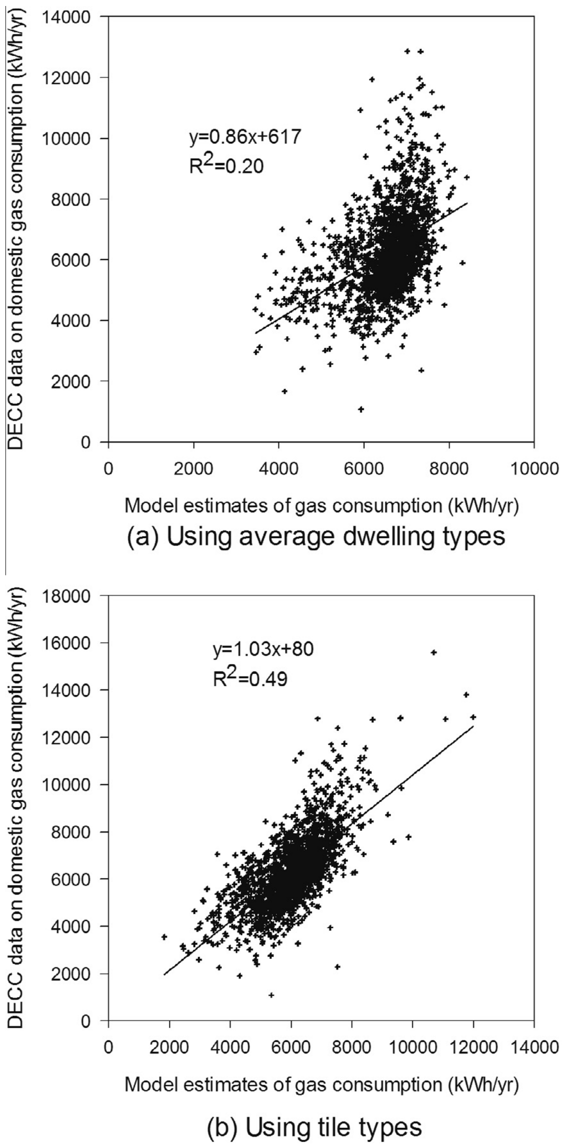

Fig. 7. Comparison of the outputs against gas consumption data.

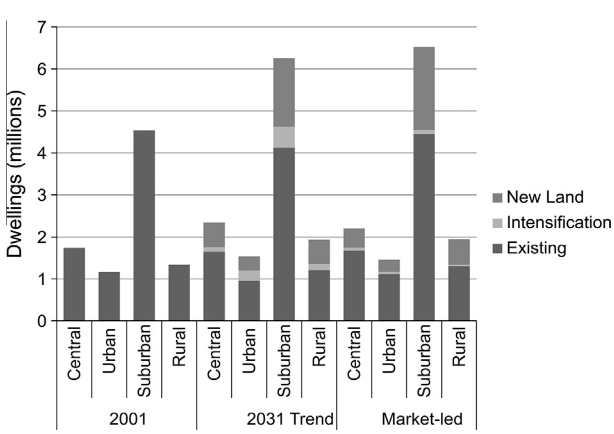

Fig. 8. Provisional forecasts of dwellings per area type – Trend vs. Market-led spatial options.

have ground source heat pumps (GSHP) in these area types (see Appendix A). It can be seen that for the Trend spatial option, both technology scenarios would have broadly similar overall CO_2 reductions per capita. However, for the Market-led spatial option the GSHP would have a much bigger reduction in CO_2 than DH because the GSHP would be more suitable for lower density areas. Similar comparisons could easily be produced for the technology costs, and for different assumptions about their suitability, performance and economies of scale.

5. Discussion

The presented modelling framework has successfully integrated the forecasts of regional residential densities with the testing of decentralised energy scenarios at the building scale. It has the potential to improve the reliability of carbon reduction strategies by forecasting how the variability of residential space, dwelling characteristics and occupancies would affect the future uptakes and suitability of building-scale energy technologies. This modelling framework has the potential to be further developed by including a wider variety of scenarios and the modelling of energy demands and supply per tile type in more detail.

Our initial uptake assumptions were quite modest and based on our conservative estimates informed by the literature at the time of carrying out the research. The uptakes were then further refined by considering the suitability of urban form at the building scale. As a result, our findings show only a marginal reduction in CO_2 emissions. This differs from Committee on Climate Change advisory reports and the Future of Heating report that anticipate decentralised heating to be a major part of the UK carbon reduction strategy. Our method provides a more realistic estimate of the potential contribution and performance of these technologies because it takes into account at the building-scale the space available and how this would affect their suitability and the demand and supply balance. It thereby can provide a more realistic estimate of the future carbon reduction and abatement costs and how these would vary spatially within the regions, depending on planning policies. Sensitivity testing could easily be carried out as further research for different initial uptake assumptions, costs, performance and efficiencies.

The cost calculations are based on the investment and operating costs of each energy scenario, compared to the prices of conventional energy supplies. We set out to assess the investment case for developers of properties and their energy systems, and not to take a least-cost view of the UK's energy system. This reflects the decisions that would face households and developers if using their own investment criteria to decide between either unsubsidised local generation, or paying market rates for buying conventional energy supply. We have excluded consideration of policy support that might be available to lower carbon options throughout the period; in reality such support will improve the commercial prospects of all the lower carbon options. Policy support of some sort is likely to exist, seeking both to capture the positive social externalities of innovation and to reflect the environmental externality benefits of lower carbon technologies. However uncertainty in levels and continuity of policy support infers significant policy risk and thus reduces its influence on investment decisions. The regional modelling framework has the potential to explore how best to target policy support for each technology, such as by area type, development type or dwelling types.

The recent relaxations in planning constraints in the UK means that increasing numbers of houses are being built in outer areas and planning policy is becoming more 'market-led.' This will tend to increase the floor space and car travel per capita and hence CO_2 emissions. It would be more cost effective to offset these higher emissions by retrofitting large older houses or housing estates rather than investing in decentralised supply for New-build.

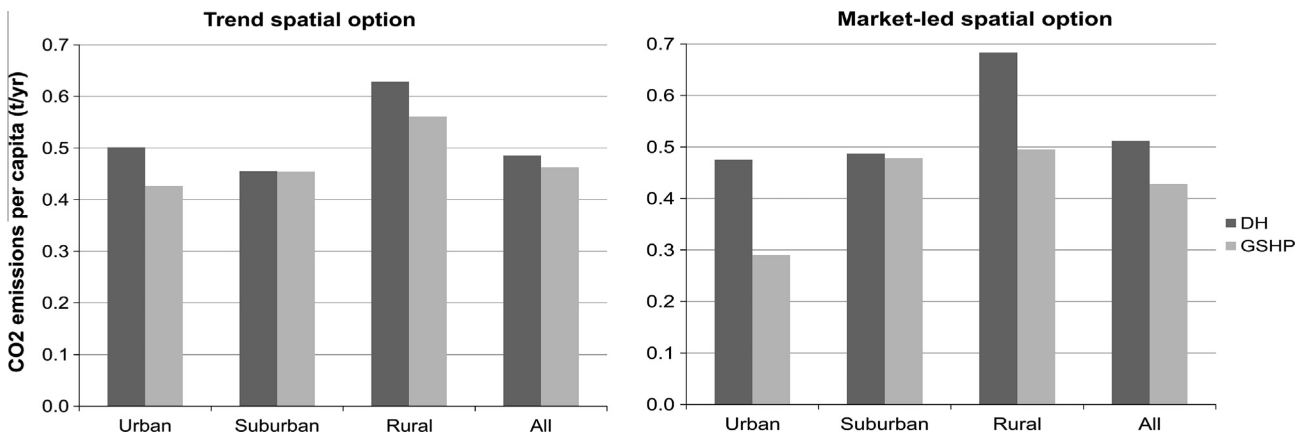

Fig. 9. CO_2 emissions per spatial option – DH vs. GSHP per area type.

Developers may be best placed to implement such a policy by retrofitting areas surrounding their new developments.

The modelling framework could be used to assess what depth of retrofitting and which types of decentralised supply would be suitable for different parts of the region. This would provide an improved basis for policy support but the actual design and assessment of schemes would need to be carried out on a site specific basis.

6. Conclusions

This paper has demonstrated a novel method of improving the regional spatial modelling of residential energy consumption and the potential for decentralised supply. This combining of regional, urban and building scale modelling within an integrated framework is a new and innovative method. It can forecast how spatial planning policies would affect the suitability of retrofitting and decentralised supply and how this would vary between area types.

Our method substantially improves the spatial estimates of energy consumption compared to building energy models that use standard dwelling typologies. Our modelling framework can forecast the impacts of alternative spatial planning policies on the future potential of decentralised energy supply. For example, it shows how lower density development would be more suitable for GSHP. The impacts on carbon reduction and supply costs can be aggregated from local to regional scale.

Our findings are important because this method would help to improve the evidence base for strategies on achieving carbon budgets. Currently these strategies do not adequately take into account how future residential space constraints would affect the suitability and uptakes of these technologies and our method could substantially improve these estimates.

Our results show that the retrofitting of dwellings to improve their energy efficiency would be cost effective and could give a positive rate of return on investment especially for the larger dwellings of lower density areas. However, most of the decentralised supply technologies tested would not be cost effective in 2031, based on the simplifying assumptions made for the purposes of this study that in real terms the future costs remain similar to those of today.

For Existing dwellings in 2031, ground source heat pumps would be poor value for money (carbon abatement cost of around £400/tonne). Biomass and gas would provide a greater reduction in CO_2 than heat pumps but would still not be cost effective for reducing CO_2 emissions (around £200/tonne). Micro-CHP & gas would be cost effective (within £70/tonne).

For New-build dwellings, the fabric improvements to achieve CfSH Level 4 would give a marginal return on investment compared to the Part L 2006 buildings standards. Resistive electric heating would not be cost effective in 2031 compared to conventional gas heating but it may have a carbon reduction benefit in the longer term as decarbonisation of the grid continues. Electric prices would need to become relatively cheaper to make it financially attractive. District heating was the example of CHP technology tested for New-build but its high costs would make it financially unattractive without policy support. The expected high levels of energy efficiency of New-build and decarbonisation of the conventional supply would allow very little scope for further reduction in CO_2 emissions to justify the cost of decentralised energy supply.

Our testing of district heating was based on estimates of the typical cluster size and density per area type without taking into account different economies of scale, and as such is only suited to a broad relative comparison between widely differing supply options. This did not take into account location specific characteristics of residential developments such as a hospital or industrial area heat source that may make district heating more cost effective. Also, the decentralised energy supply was selected to meet the dwelling requirements and it may have been more cost effective if operating at a surplus to supply a wider area.

As conventional electric supply is decarbonised and the energy efficiency of dwellings improves, decentralised energy supply will become even less financially attractive over time. Their uptake is therefore likely to decline unless there is continued policy support and without subsidies most of the technologies tested would not be cost effective for developers to install compared to the prices paid for conventional supply.

The method reported in this paper could help to improve the forecasting of which technologies would be the most promising for the future. It could explore ways of targeting policy support spatially by area type, although the actual design and assessment of schemes would still be need to be done on a site-specific basis.

Our method and findings could be used to explore spatially within the city region the most suitable combinations of built form, building fabric and decentralised supply. This may provide evidence for urban design on the most suitable combinations of dwelling types, densities and clustering for energy systems. Local planning authorities could then aim to achieve these suitable characteristics through their local development frameworks and thereby take a 'bottom-up' approach to achieving long-term energy policy targets. The aim would be to achieve a co-ordinated approach where both the national top-down strategies for carbon budgets and the bottom-up planning and regulations

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of the districts are complementary. Other sectors such as water, waste and transport could also be included within this integrated modelling framework. Our methods and findings could provide planners and practitioners with the evidence to put in place planning policies and regulations to safeguard the residential space needed for the future installation of the most promising decentralised technologies. The schemes could then be planned, assessed and designed in more detail on a site specific basis as part of local urban energy planning. The method could also be extended to include non-domestic buildings. Exploring these relationships between urban form, energy consumption and the potential for decentralised energy supply could lead to a clearer understanding of how urban planning and densities will affect urban metabolism as decentralised energy conversion become more prevalent in future.

The next step for this research will be to explore the technology design and uptakes in more detail per tile and apply the method to other case study regions and aim to validate the findings against operational schemes. Future costs and performance could be considered in more detail and the range of uncertainties explored by sensitivity testing. The assessment could be broadened to consider the energy supply system as a whole and expanded to include broader aspects of regional development, such as embodied energy and urban energy planning.

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Appendices. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.02.095.

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